STUDIES WITH SMALL RIVER MODELS

VOL. I OF 2

R. K. DEEPROSE

APRIL 1959

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STUDIES WITH SMALL RIVER MODELS

A DISSERTATION

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

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BY

R.K. DEEPROSE

UNDER THE DIRECTION OF

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APRIL, 1959

ABSTRACT

The principal object of the work described herein was to attempt the running of some conventional very small scale river model tests in a manner that would permit the application of regime theory to quantitative predictions. The admitted inadequacy of the University's very small river tray for accurate practical quantitative predictions, unaided by field experience, is irrelevant to this purpose. The potential value of the work lies in the creation of situations suitable for analysis and in the presentation, for the reader's criticism and consideration, of their descriptions and tabular analyses; in particular it is hoped that the chronological recording of events under very complex circumstances may be useful to future workers who wish to approach the unsolved problem of using models for predicting rates of development of phenomena. The results are not intended to have any immediate exact practical quantitative application.

The tests run to achieve the main purpose were chosen to cover the field of known successful qualitative work of major practical application, and to suit the facilities of the University river tray. They were:-

i. Study of a topical river scour problem, where a slide had affected a bridge.

ii. Study of some rather idealised spur situations.

iii. Study of an assisted cut-off.

Quantitative discussion of the tabulated results would form a thesis subject in itself and so has only been touched briefly here.

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April, 1959.

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NOMENCLATURE

Standard units are foot, pound and second.

b	mean breadth at a section.
C	charge, a measurement of the amount of bed load transported by a stream, measured in parts per hundred thousand by weight of water flowing.
cfs.	cubic feet per second.
d	mean depth at a section.
d_s	scour depth, i.e. depth of hole below water surface.
d_{fo}	zero flood depth; a regime parameter $= \frac{V^2}{F_{bo}} = \frac{q^{2/3}}{F_{bo}^{1/3}}$
d_r	regime depth $= \frac{V^2}{F_b} = \frac{q^{2/3}}{F_b^{1/3}}$
D_m	median diameter of bed material grains in milimeters.
F_s	side factor; a regime parameter $= \frac{V^3}{b}$
F_b	bed factor; a regime parameter $= \frac{V^2}{d} = \frac{q^2}{d^3}$
F_{bo}	zero bed factor; a regime parameter $= 1.9 D_m^{1/2}$
Q	discharge rate in cfs.
q	discharge intensity $= \frac{Q}{b}$

NOMENCLATURE - continued

S	slope of water surface in channel.
V	mean velocity at a section.

CHAPTER 1

INTRODUCTION

Hydraulic Models

The requirements to be met in the manufacture and operation of a so-called dynamically similar model are that the model and prototype be geometrically similar and also have the forces acting on them in fixed ratios. This latter requirement means that in an hydraulic model the same ratios must occur between the forces of gravity, viscosity and surface tension as in the prototype. It is rarely, if ever, possible to satisfy both these requirements completely, simply because the ratios between nature's forces usually depend upon the size of object that the forces act upon. A simple illustration of this is the case of a needle floating on water in a saucer, held up by surface tension; the 'prototype' of this might be a crowbar set upon the surface of a lake. The model is geometrically similar but not dynamically similar since in the prototype the force of gravity far outweighs the force of surface tension.

In spite of the usual impossibility of producing an exact model, rigid-boundary geometrically-similar hydraulic models have become widely used. There are two reasons for this. Often a model is concerned with only one or two dominant characteristics of a prototype so these are reproduced in scale while the other requirements for an exact model, if unimportant, are ignored. For example, when flow is highly turbulent,

as in model and prototype of open channel flow, viscosity forces have a negligible effect on friction factor and need not be scaled for certain purposes. The second reason is that information on numerous comparisons between model predictions and prototype behaviours has been shared widely among experimenters. This store of theoretical and practical knowledge has made it possible for any hydraulic engineer who acquaints himself with the necessary literature to know the types of rigid-boundary hydraulic model study that will be practically successful.

Mobile-boundary models, i.e. models in which the moving water can alter its own boundaries by erosion or deposition (e.g. river models), have been found to be far more complex than rigid-boundary ones. This greater complexity is largely a result of the impracticability of scaling down the particles that are found on the sides and bed of a natural river. If the gravel and sand were scaled down geometrically in the same ratio as the other dimensions of the river then the resulting particles would usually be in the clay-size range and while the natural non-cohesive sand and gravel rolls or jumps along the bed the cohesive clay would either refuse to move or would be removed in suspension. Model and prototype action would, therefore, not correspond at all. Accordingly, there cannot be geometrical similarity of the boundary material and the interpretation of a model study, now not "dynamically similar", must be left to an expert on river engineering. Large models are more accurate but still not problem-free and are much slower acting than small models. This slowness often makes them impractical since

many problems brought to the attention of model makers require immediate answers.

A survey of the literature on mobile-boundary models reveals that no general agreement on methods of scaling these models exists even among river engineers (as does for rigid-boundary models). In fact, a controversy rages. (Refs. 1 & 2) The greater complexity of mobile-boundary models is, of course, a big reason why the subject is still in the realm of controversy. Another important cause of the relative backwardness of river model work is the length of time and difficulty connected with proper, detailed prototype observation. While rigid-boundary hydraulics deals with prototypes such as weirs, lined canals, pumps, turbines, etc., in which the operating conditions are man-imposed and therefore known, the prototypes of mobile-boundary hydraulics are usually natural phenomena and the operating conditions are imposed by the vagaries of nature. A day's or week's observation of a weir may include all the conditions under which the weir is expected to flow, while ten years of observations on a river could very well be but a glance at a never-ending process. The mobility of the boundaries makes it necessary that a great many more quantities and facets be observed than is the case for rigid-boundary hydraulic structures. For these reasons no large pool of accurate observation and comparison exists for mobile-boundary model hydraulics as does for rigid-boundary models. Therefore, vast amounts of careful qualitative

and quantitative field and lab observations are necessary before the average engineer can successfully undertake river model work.

The greatest need now is for quantitative model study of a general nature so that the validity of general laws of model scaling can be verified. The solving of specific practical problems only, with models, often adds but a fraction to general knowledge because the model maker is then interested only in the solution of one or two matters. If observations of all physically relevant phenomena were carefully recorded, whether immediately useful or not, analysts of model behaviour would have a much larger fund of information.

Some excellent qualitative model work has been done on certain subjects, e.g. Friedkin on meandering (Ref. 3) and Leopold and Wolman on braids (Ref. 4). Numerous investigations of shoaling problems have been carried out at the Waterways Experiment Station at Vicksburg, Mississippi. Ake Sundborg's field work (Ref. 5) on some items of river self-formation merits mention as does the excellent quantitative field work being done by Leopold and Associates (Refs. 4, 6). This is only a start, though, and quantitative linkage of field to model remains speculative.

Work Covered by Thesis

Although river model research is handicapped by uncertainty as to correct scales and reproduction of prototype behaviour and also by

the absence of accepted and proven techniques, the research worker is at liberty to study almost any river phenomenon qualitatively without duplicating the work of others.

The most useful study that could be done in the time allotted for the work was judged to be an investigation in which a large amount of data on various phenomena could be collected.

The thesis work centered around three separate experiments:

(1) a model study of a specific river problem in which an attempt was made to predict the effect of certain engineering actions on the river,

(2) a study on scour around river spurs under special circumstances,

(3) a study of the development of an assisted cut-off.

For the reasons given already, observations were not confined to the specific problem posed for each test, but ranged over as wide an area as possible in hopes that the careful compilation of available data would point the way to improved quantitative comparisons between model and prototype in mobile-boundary hydraulics and might provide information that could be useful along with material yet to be collected.

Special reasons for the choice of these three experiments were: (1) the attempt to predict the action of a particular river focuses attention on inevitable distortions, (2) spurs are important river training devices and although some facts are known about their maximum

scours little is known about the effect on scour of shape and orientation, (3) general qualitative meander work has been done by Leopold and Friedkin, (4) assisted cut-offs are being used now by the Government of Alberta in the field, (5) all these experiments could be attempted with a reasonable hope of qualitative success in a small model.

Thesis Presentation

Chapters 2, 3 and 4 treat each experiment separately, containing detailed descriptions of procedure, tabulation of data, and such conclusions as may be drawn at present, in answer to the specific problem in hand. Chapter 5 compares data and observations from all three experiments with each other and with recorded results of other investigators. The appendix contains a record of various techniques used during the model study, some of which finally bore fruit after long hours of ironing out difficulties, and others which the author found to be failures. The space given to various matters of technique reflects the amount of time and effort spent in learning the most satisfactory methods of operation. Even the list of failures should be valuable in that it may offer a challenge to others to overcome the difficulties explained, while warning of pitfalls.

Apparatus Common to All Work

River tray The river tray at the Civil Engineering Building, University

of Alberta (Ref. 9), is 20 feet by 50 feet in plan and holds about a 10-inch depth of sand. Two pumps with a combined total discharge of approximately 0.8 cfs. recirculate the water from the tray outlet back through the tray again. A small stilling basin at the entrance to the tray dampens out momentary fluctuations in the pump discharge. A larger basin at the tray outlet acts as a trap for sand being swept out of the stream channel before the water is led back into the pump. The inlet and outlet to the tray are both on the longitudinal axis of the tray. Both are 18 inches wide. The outlet elevation is about 3 inches above the floor and the inlet is a few inches higher. A baffle composed of a piece of plywood drilled with closely spaced 3/8-inch holes covers the inlet. The discharge from each pump is led over a 90 degree v-notched weir. A hook gauge set 8 inches back from the notch measures the head over the weir. The approximate formula giving the discharge over a v-notched weir was not considered to be of sufficient accuracy for these experiments so one of the weir boxes was calibrated both by connecting it to a 3-inch rotameter and by a time-volumetric measurement of discharge through it. The latter calibration was assumed correct for both weir boxes. For the record of the above-mentioned tests and an attempt to obtain continuous discharge readings see the Appendix; Section B.

Figures 24 and 66 are photographs of the river tray.

Figure 23, a map of the model river, shows the numbering system along the edges of the tray. The top end of the tray (north end) is

numbered zero feet and the south or bottom end is 46 feet. In the other direction the 10-foot mark is on the N-S centerline, 0 marks the western edge and 20 the eastern edge. Positions in the tray are referred to, for example, as N-S 35.0, E-W 7.5.

Sand feeder (see Fig. 1) A large wooden hopper leads sand into a mechanical device for dropping sand at a specified rate into the channel at the head of the river tray. A sliding cam gives a range of rates of 4.5 to about 90 lbs. an hour.

The sand used in the feeder was oven-dried and freed of lumps by passing it through a number 4 sieve.

CHAPTER 2

MODEL STUDY OF THE PEACE RIVER AT TAYLOR FLATS

Introduction

Problem As mentioned in Chapter 1, an attempt was made to predict happenings consequent on a projected engineering action. The site chosen was that of a bridge over the Peace River, an incised river of about 400,000 cfs. peak discharge, bed material sand and gravel, charge believed negligible, sides mainly shaley, very little meandering and very little flood plain (information on character of river from Professor T. Blench). Figure 11 shows a map of the bridge site. A pump house has been built recently west of the bridge. A recent slide on the north bank had damaged the bridge and produced an upheaval of the river bed in the zone marked off by the dotted lines.

The proposal for stabilizing the slide was to weight the toe of the slide with soil and then rip-rap the built-up area to protect it from being eroded away. Two different shapes of slide protection were under consideration, a short broad area extending part way out to the pier and a longer one reaching out to enclose the same pier (Fig. 15 and 16). The problems were: (1) would the constriction of water flow endanger either bridge pier by concentrating its erosive force, (2) would the region at the entrance to the pumphouse (Fig. 11) silt up as a result of the presence of the built-up area immediately downstream?

An immediate answer was necessary therefore a large detailed model requiring several months of operation would have been out of the question.

Expected results Although the ultimate decision on the possible danger to piers and pumphouse inlet had to be made by an experienced river engineer the model study was likely to give at least a qualitative answer as to the outcome and, in addition, had the merit of giving the author an opportunity to assess the practical difficulties of making and using quantitative measures in the particular model and in river models in general. The ability to recognize imperfections is necessary for forecasting stream behaviour and for devising improvements in technique.

Nature of model stream, regime considerations While, as has been indicated, insufficient knowledge of river behaviour has prevented the formulation of accepted rules to guide model builders, much is known about the character of canals. The laws governing the behaviour of canals are known for a special but common case, that of canals in regime. These waterways are mobile-boundary canals that do not change their average behaviour over a period of a score of years or so and that move a bed load of non-cohesive material in dune formation. That is, discharge, load, slope, width and depth remain practically constant. For a comprehensive explanation of the concept of 'regime' and 'in regime' see Ref. 7.

For the purposes of this chapter it is sufficient to note that when channels in regime are being compared it is the fact that both are in equilibrium that is the necessary common factor. The other characteristics of streams are related through, and because of, this prior relationship. Thus gravel-bed channels can be compared with sand-bed streams and, as in the following case, a river carrying a small bed load compared with a stream transporting a relatively greater bed load. While erratic changes in river discharge prevent a river being visualized as closely in regime as a canal, rivers do frequently approach a condition of average long-term equilibrium (i.e. the bed and sides do not show an appreciable average change, and neither continued aggradation nor degradation takes place.)

It should be noted that suspended load is not a factor dealt with by quantitative regime theory; but suspended load will deposit to form berms in excessively wide channels and alter apparent viscosity of the fluid. The absence of a suspended load from the present model will affect only long-term berm building so is un-important.

For two reasons it was deemed necessary for the model river to be in regime at the beginning of the experiment. (1) Although rivers never have a constant discharge they may often be graded, i.e. neither aggrading nor degrading therefore maintaining constant width and slope. As noted on page 23 the Peace River seemed to be neither aggrading nor degrading except for the activity occurring at the time of a very high flood. (2) When a stream is in regime a number of variables, known,

and unknown, are eliminated so that happenings can be compared more easily to other regime waterways. The preliminary work, therefore, consisted of starting a stream running through the river tray and waiting until it settled down into a state of equilibrium.

Special Materials

Sand The tray originally had been divided into two longitudinal compartments with different-sized sand in each. Subsequently lumps of clay had been mixed with the coarser sand to the west in an unsuccessful effort to form a river bank material similar to that found in nature. The lumps of clay ranged from pea size up to about two inches in diameter. The finer sand on the east side contained only occasional pieces of clay and those were close to the centre of the channel. The grain size analysis of each is shown in Fig. 2, which is a composite of Plates 7 and 8 of Ref. 9.

Preliminary Work; Creation of a Stream in Equilibrium

Method- A straight channel, 18 inches wide and about 6 inches deep was cut down the centre of the tray. This left fine clean sand on the east side and the coarser sand and clay on the other. After the water had been turned on so that irregularities became apparent by the depths of water along the channel the bed was smoothed so that the water flowed over the entire width of bed. The reason for using a straight channel was to permit

the compilation of a log (Table 1) of developments from a straight to a meandering channel for analysis by future investigators.

The desired flow of 0.09 cfs. was imposed gradually in order that no initial rush of water would greatly change the shape of the channel immediately. Starting with a flow of 0.01 cfs. the discharge was increased in increments of 0.01 cfs. approximately every 8 hours until 0.09 cfs. was reached. When it was discovered that the channel would not adjust rapidly to a slope at which no sand was being transported a suitable charge was introduced into the top end and the model was run until the charge of sand coming out of the bottom was equal to that being fed in at the top. At this stage it was assumed that no marked aggradation nor degradation was occurring and that the average charge in every part of the channel was the same.

Measurements taken The amount of sand per hour leaving the bottom of the channel was measured by regularly emptying the outlet basin of sand, drying it and weighing it. A series of calibrations was run on the sand feeder to determine how much sand was entering the river tray for given positions of the cam.

The water surface elevations and therefore the slope, were measured by a surveyor's level and a small rod which had a short piece of wire attached to the bottom; when the wire just touched the water surface a small disturbance could be seen. The rod was either attached to the scraper on the gantry (Fig. 24) so that it could be held firmly and moved

up and down slowly, or it was held by a person who steadied it against the gantry. Measurements were accurate to within a millimeter except when surface waves were larger from crest to trough than this.

Cross-sections of the stream were obtained by measuring the depth of water at short intervals across a section. The depth is liable to an error up to 0.1 inch since it is very difficult to sense the exact depth in loose sand under water.

Record of development Table 1 is a chronological record of the changes that took place in the river tray while the stream strove to reach a state of equilibrium.

Note that a charge of 1 for Q= 0.09 cfs. = 0.20 lbs./hr.

Note that the line down which the elevations were taken was at the 10.3 ft. mark, (see Fig. 23) 0.3 ft. east of the centre line of the tray.

TABLE 1

CREATION OF A STREAM IN EQUILIBRIUM

Time	Interval	Q	Remarks	Charge	
				Leaving Tray	Entering Tray
Hrs.	Hrs.	Cfs.			
0		0.01	Stream progressed only half way down channel since much water soaked into the dry sand.		0
	0.25				
0.25		0.02	Channel about 6" wide.		
	1.65				
1.9			Pump stopped for repairs.		
1.9		0.02	Channel width about 5" where it had cut down. Bottom levelled so that water flowed over full 18" width.		
	2.0				
3.9			Stream running about 9" wide with a meander length of 5' over a high spot in the channel. Where flow full width meanders still evident by channels of greater depth winding over bed.		
6.9			Meander had disappeared.		
	1.5				
8.6					0

TABLE 1 - continued

CREATION OF A STREAM IN EQUILIBRIUM

Time	Interval	Q	Remarks	Charge	
				Leaving Tray	Entering Tray
Hrs.	Hrs.	Cfs.			
8.6		0.03	As soon as Q increased movement of bed material became easily apparent with some immediate dune formation in steeper portions.		0
	10.3				
18.9			Distinct dune formation except in deep areas. Average dune height 1/2". Scour holes as deep as 1" formed around clay lumps. From Sta. 20-42 there were deeper channels down both sides of the river bed but the water was following only one of these paths. Meander length 13'. 2" long, fairly rapidly moving dunes formed along paths of greater flow. Tendency shown to swing toward east side of tray where the sand was finer.		
	0.5				
19.4		0.035			
	6.7				
26.1			Meander length about 10' from Sta. 25 to 44. Dunes from 3"-9" long.		
	0.3				
26.4					0

TABLE 1 - continued

CREATION OF A STREAM IN EQUILIBRIUM

Time	Interval	Q	Remarks	Charge	
				Leaving Tray	Entering Tray
Hrs.	Hrs.	Cfs.			
26.4		0.045	Bed movement became more obvious with higher velocity.		0
	7.6				
34.0		0.055			
	8.9				
42.9					
	0.5		Average depth Sta. 0-10= 1". River banks 4" - 5" above water surface all along stream. Two barchan dunes at Sta. 7, length 6" width 4"-5". Height 3/4"-1".		
43.4		0.06			
	7.7				
50.1					0

TABLE 1 - continued

CREATION OF A STREAM IN EQUILIBRIUM

Time	Interval	Q	Remarks	Charge	
				Leaving Tray	Entering Tray
Hrs.	Hrs.	Cfs.			
50.1			Lumps of clay lined the west side of the channel while on the east side clay found only in the upper portion. Constriction at Sta. 13 caused by large lumps of clay on both sides.		0
	0.2				
50.3		0.07			
	7.3				
57.6			Average depth of channel approx. 1"-1 1/4" where width = 20" - 24". Flow concentrated along west bank Sta. 31-46.		
	0.2				
57.8		0.09			
	14.2				
72.0			Flow concentrated along west bank from Sta. 21 to 40 but clay seemed to be preventing erosion of that bank. East bank being continually eroded.		
	0.5				
72.5		0.09			
	3.0			60	
75.5					0

TABLE 1 - continued

CREATION OF A STREAM IN EQUILIBRIUM

Time	Interval	Q	Remarks	Charge	
				Leaving Tray	Entering Tray
Hrs.	Hrs.	Cfs.			
	5.0			57	0
80.5			Water appeared to be concentrated along the west side where the dunes were short and moving rapidly but soundings proved that side of the channel to be no deeper than the rest.		
92.0			Levels taken of water surface. (Fig. 3) A difference of 0.22 cm. read between the top and trough of a wave at Sta. 24. The accuracy of this reading is difficult to determine; however, waves estimated to be 0.2 - 0.4 cm. high.		
80.5					
	13.0			37	
93.5					0
	4.9				
98.4					

TABLE 1 - continued

CREATION OF A STREAM IN EQUILIBRIUM

Time	Interval	Q	Remarks	Charge	
				Leaving Tray	Entering Tray
Hrs.	Hrs.	Cfs.			
	6.7			51	0
105.1					
	13.2			30	
118.2					
114.9		0.09	No change evident. Channel still narrow where banks protected by clay lumps.		
120.4			Cross-sections taken down the stream at points of change. (See Figs. 4, 5, 6.)		
126.8		0.09	Levels taken of water surface. (Fig. 3)		
118.2					
	9.4			29	
127.6					
	14.1			22	
141.7					
	5.0			19	
146.7					0

TABLE 1 - continued

CREATION OF A STREAM IN EQUILIBRIUM

Time	Interval	Q	Remarks	Charge	
				Leaving Tray	Entering Tray
Hrs.	Hrs.	Cfs.			
	16.3			19	0
163.0					
	7.7			20	
170.7					
	16.4			16	
186.1					
	7.8			12	
194.9					
	16.6			9.3	
211.5					
	47.8			6.8	
259.3					
	23.9			6.4	
283.2					
	24.0			7.7	
307.2					0

TABLE 1 - continued

CREATION OF A STREAM IN EQUILIBRIUM

Time	Interval	Q	Remarks	Charge	
				Leaving Tray	Entering Tray
Hrs.	Hrs.	Cfs.			
	24.0			6.1	0
331.2					
	24.1			6.7	
355.2		0.09			
	24.0			5.6	
379.2					
382.2			Sand feeder started at this time at lowest rate possible which equalled a charge of 22. Difficulty experienced in getting sand to spread evenly over stream bed so that all sand would be carried away. See appendix for complete account of solution of this problem.		22
379.2					
	48.0			6.4	
403.2					
	24.0			17.	
427.2					22

TABLE 1 - continued

CREATION OF A STREAM IN EQUILIBRIUM

Time	Interval	Q	Remarks	Charge	
Hrs.	Hrs.	Cfs.		Leaving Tray q	Entering Tray
	24.1			25	22
451.3					
	24.1			32	
475.4					
482.9			Water surface elevation measured. (Fig. 7)		
	24.0	0.09		34	
499.4					
	24.0	less than 0.09	For two or three hours during this period only a fraction of the full discharge flowing because of technical difficulties. Sand feeder turned off for exactly one hour.	30	
523.4		0.09			
	48.1			23	22
547.5			Stream judged to be in equilibrium.		

Attainment of equilibrium When finally the amount of sand coming out of the bottom of the stream equalled the amount of sand being fed into the top, the stream was judged to have reached a state close enough to equilibrium for the Taylor Flats model study. The sides were still eroding a little where they were not protected but the model was to deal with bed scour, not bank caving, because the Peace River banks are relatively stable.

Effect on Scour of Proposed Alterations to Peace River

Basic data of Peace River site:

A From maps: (Fig. 11)

River width at bridge	1560 ft.
Width of piers	20
Length of piers	50
Distance from shores to piers	320
Distance from north shore to toe of slide	200
Length of slide area	725
River bottom elevation	1307 - 1308

B From study of river discharge and stage:

Years of record	1944 - 54
Highest recorded discharge	406,000 cfs.

Water surface elevation at 406,000 cfs.	1339 ft.
Depth for record discharge	31
Average monthly flow during active months (May - December)	66,000 cfs.
Water surface elevation at 66,000 cfs.	1323.5
Depth for average flow	16
Elevation of top of slide protection	1330

Except for the period of high flood in 1948 when the river stage increased nearly one foot at almost all discharges and then lowered one-half foot again the gauge-discharge relation remained practically constant.

Model procedure Two sites were selected in the tray's regime channel (just described) for a model study of the problem stated on page 9 ; they were: (a) Sta. 38 located in a comparatively straight reach where the sides had been cut away evenly in the soft sand during the previous month, and (b) Sta. 10 where a few lumps of clay had caused a constriction in the channel (Fig. 19). Each site, in plan, produced a fairly good copy of the mirror image of prototype conditions.

Choosing these two sites of different sizes gave two different model - prototype vertical exaggerations; this is useful since as has been noted (Ch. 1) there is no general agreement on scaling of mobile-boundary models. The narrow channel at Sta. 10 had the greater vertical distortion so the size of pier placed in the model was scaled according to

the horizontal dimensions. At Sta. 38 the vertical distortion was less, so as a check on the effect of vertical exaggeration the model piers were made to the same (width of pier) / (water depth) ratio as in the prototype. For the elevation of the slide area, a vertical dimension, the scale was according to the water depth in both cases while the lateral extent of the slide area, a horizontal dimension, was scaled according to the channel width in both cases. Table 2 summarizes size and scale data.

Only at Sta. 10 were the islands of the prototype placed in the stream and, here, the downstream islands were removed when they appeared to be unduly influencing the course of the flow through the second site.

Various materials for stabilizing the stream sides were tried. Table 3 gives the final types used and the Appendix, Section D, gives a full account of the attempt.

Scour depths were measured for the three cases of (1) no slide protection, (2) slide protection A, and (3) slide protection B for the 0.09 cfs. flow and again for a flow of 0.45 cfs. The flow of 0.09 was supposed to represent the average river flow since, as noted under 'preliminary work', the initial channel was formed at this discharge. The passage of 0.45 cfs. was an attempt to represent high flood conditions. It was impossible at that time to pass a flow of 0.54 cfs., which would be six times average but the depth attained with 0.45 cfs. was approximately twice the depth of water with 0.09 cfs. flowing corresponding to the

prototype ratio of 31/16 for $\frac{\text{maximum stage recorded}}{\text{average stage}}$.

The model was not irreversibly changed by the flood flow so as to adversely affect the succeeding normal flow test; a few hours spent in running it at 0.09 cfs. again re-established the average conditions. The sequence of tests chosen to avoid any one affecting those that followed is detailed in Table 6.

Cross-sections of both sites were taken at right angles to the axis of the stream (Figs. 12, 13, 14).

A map of the ultimate model river formation is in Fig. 19.

TABLE 2

SIZE OF MODEL AND SCALES USED

Sta. 10	Size	Scale
Breadth	1.85 ft.	1/1060
Mean depth	0.8 in.	1/240
Sta. 38		
Breadth	2.85 ft.	1/690
Mean depth	0.5 - 0.6 in.	1/350

Sta. 10

Horizontal dimensions of piers and of slide area scaled according to width of channel.

Pier width $\frac{20}{1960} \times 1.85 \times 12 = 0.285$ in. Size used 0.3 in.

Pier length $\frac{50}{60} \times 0.285 = 0.71$ in. Size used 0.8 in.

Elevation of top of slide protection scaled according to depth of channel.

Sta. 38

Horizontal dimensions of pier and elevation of top of slide protection scaled according to depth of channel.

Pier width $\frac{20}{16} \times 0.6 = 0.75$ in. Size used 0.75 in.

Pier length $\frac{50}{20} \times 0.75$ 1.85 in. Size used 1.8 in.

Horizontal dimensions of slide area scaled according to width of channel.

TABLE 3

BANK AND SLIDE PROTECTION

Position	Station	Discharge	Shape of Slide Protection	Stabilizing Material
Banks	10	0.09	None	Clay (on bank)
			Shape A	Clay
			Shape B	Sheet Metal
		0.45	None	Sheet Metal (on bank)
			Shape A	Sheet Metal
			Shape B	Sheet Metal
	38	0.09	None	Paper (on bank)
			Shape A	Paper
			Shape B	Paper
		0.45	None	Paper (on bank)
			Shape A	Paper
			Shape B	Paper
Slide Area	10	0.09	Shape A	Sheet Metal
			Shape B	Sheet Metal
		0.45	Shape A	Sheet Metal
			Shape B	Sheet Metal
	38	0.09	Shape A	Cardboard
			Shape B	Sheet Metal
		0.45	Shape A	Cardboard
			Shape B	Sheet Metal

Discussion of observations 1. Figure 12 shows, at Q = 0.09 cfs. the cross-sections at the two alternative Stations 10 and 38 for no slide protection, A type protection, and B type protection. For Station 38 two B type results are shown, for different times to show the extra scour resulting from allowing adequate time for it to develop. Figures 13 and 14 show the results of increasing discharge to the high flood value of 0.45 cfs. Figures 15 - 17 show corresponding plan views of the flow.

Scour Shown by Cross-Sections

2. To allow the scours shown by the section to be appreciated quantitatively two tables have been prepared. Table 4 shows maximum scoured depths without protection in inches and as 100% compared with maximum scoured depths for slide protections A and B and discharges of 0.09 cfs. and 0.45 cfs., also in inches and percentages. Table 5 shows how cross-sectional areas altered to suit different scoured conditions.

Scour Analysis

3. Partly for future quantitative use in studying rates of development of scour, and partly to permit verification that the procedure did not permit results to depend essentially on preceding ones, Table 6 is presented as a log of the whole series of events.

Chronology

4. With the lower discharge the introduction of slide

Change

protection caused scour at both piers; with the higher discharge most scour was at the north (slide) pier.

in Scour

5. Vertical distortion (as discussed in Ref. 7 p. 118) causes scour holes to occupy relatively more plan length than they would in the prototype. In the present case the scours due to slide and pier overlapped whereas, in the prototype, they would have been separate. Accordingly prophesy about the prototype is not possible with any exactness in this overlap zone.

Vertical Distortion

6. Although cross-sectional area should increase when a regime channel is constricted the increases recorded in Table 5 are more than might be expected from this effect and may be due partly to the vertical exaggeration affecting the form of scour holes.

Areal Increase

7. The flow concentrated along both banks (see Figs. 15 - 17) in all experiments.

Flow Concentration

8. In addition to item 5, obvious model defects that prevent exact quantitative predictions were:-

(a) The flow and scour in the south part of the model at Sta. 10 were obviously influenced by the islands upstream (see Fig. 19), particularly when islands and bank were covered with sheet metal.

Model Defects

(b) Surface waves up to 0.4 inches from crest

to trough occurred when Q equalled 0.45 cfs. so measurements were not very reliable.

(c) Smooth rigid boundaries appeared to cause deeper scour than the rougher materials.

(d) Measurements of depth by a metal measure were vitiated by it sinking possibly up to 0.1 inch into the sand.

(e) Time predictions, as explained in Ref. 7, p. 119ff, are affected by charge so would have to be interpreted very carefully.

Practical deductions 1. The following predictions as to the consequences of placing slide protection on the unstable area at Taylor Flats are made on the basis of the model study:

(a) The contraction of water flow in the Peace River caused by the slide and the rip-rap placed over it will cause an increase in scour around the bridge piers especially marked in the vicinity of the slide and the north pier. Standard methods for calculating depth of scour based on constricted width and discharge (Ref. 7, p. 105) will give a better estimate as to the scour which might occur than will extrapolation from the model depths because of distortion near the banks of the model.

(b) The pumphouse inlet will not silt up unless approach conditions change considerably. (Perhaps this experiment was not run for a long enough time. In another experiment described in Chapter 4, the area

in front of a projecting spur gradually shoaled in).

(c) A shoal may be expected to form in the river immediately downstream from the slide.

2. (a) A model maker must recognize the fact that scour hole extent will be out of proportion when scaled up from a model.

(b) Until some material can be found which, when used in a model, will simulate the interaction between the gradually erodible sides of a real river and the water flowing in it models will indicate greater scours near rigid banks than those at the edges of clay-bank rivers.

TABLE 4

COMPARISON OF MAXIMUM SCOUR DEPTHS IN TAYLOR FLATS MODEL

Flow Cfs.	Station	Slide Protection	Pier	Scour Depth in.	% of Scour Depth For No Protection	Experimental Time Intervals hrs.
0.09	10	None	N	1.4	100	1
			S	1.3	100	
		A	N	2.0	145	5
			S	2.0	155	
		B	N	3.1	220	13 3/4
			S	2.0	155	
	38	None	N	1.2	100	1
			S	1.3	100	
		A	N	2.0	168	7
			S	2.1	160	
		B	N	2.9	240	14
			S	2.1	160	
0.45	10	None	N	3.3	100	1 1/4
			S	4.2	100	
		A	N	4.0	120	2
			S	3.4	80	
		B	N	6.5	195	2
			S	4.0	95	
	38	None	N	3.1	100	1 1/2
			S	2.7	100	
		A	N	3.8	120	1 1/2
			S	2.3	85	
		B	N	5.2	170	1 1/2
			S	2.7	100	

TABLE 5

CROSS-SECTIONAL AREAS AT PIERS

Flow Cfs.	Station	Protection	Area Ft.^{2}	Surface Width Ft.	Mean Depth Ft.
0.09	10	None	0.135	1.85	0.07
		A	0.16	1.55	0.10
		B_2	0.175	1.4	0.12
0.09	38	None	0.19	2.75	0.07
		A	0.21	2.45	0.08
		B_2	0.22	2.15	0.10
0.45	10	None	0.38	1.7	0.22
		A	0.36	1.95	0.18
		B	0.48	1.7	0.28
0.45	38	None	0.41	3.05	0.13
		A	0.43	3.05	0.14
		B	0.54	3.05	0.18

TABLE 6

TAYLOR FLATS MODEL CHRONOLOGY

Type of Slide Protection		None	None	A	A	A	A	A	A	A	B	B	B	B	B	None	None	None
Discharge	Cfs.	0.09	0.09	0.09	0.09	0.09	0.45	0.45	0.45	0.09	0.09	0.09	0.09	0.45	0.45	0.45	0.45	0.45
		Piers Set In Place.		Protection A Set In	Water Surface Profile.		Q Changed To 0.45 Cfs.			Q Changed To 0.09 Cfs.	Protection B Set In.			Q Changed To 0.45 Cfs.		Slide Area Removed		
STATION 10																		
Water Level	in.				43.3				43.9		43.3							43.8
Bed Elevation																		
N. Pier	in.		41.9			41.3		39.9				40.6	40.2		37.3		40.5	
S. Pier	in.		42.0			41.3		40.5				41.3	41.3		39.8		39.6	
Mean	in.		42.4			42.1		41.7				41.7	41.8		40.4		41.1	
Max. Scour																		
N. Pier	in.		1.4			2.0		4.0				2.7	3.1		6.5		3.3	
Depth S. Pier	in.		1.3			2.0		3.4				2.0	2.0		4.0		4.2	
Mean Depth	in.		0.9			1.2		2.2				1.6	1.5		3.4		2.7	
Time		Dec.9 1:30 P.M.	Dec. 9 2:30 P.M.	Dec. 9 4:15 P.M.	Dec. 9 5:00 P.M.	Dec. 9 9:30 P.M.	Dec. 10 2:00 P.M.	Dec.10 3:50 P.M.	Dec. 10 4:00 P.M.	Dec. 10 7:00 P.M.	Dec. 10 7:45 P.M.	Dec. 10 9:45 P.M.	Dec. 11 9:30 A.M.	Dec. 11 10:00 A.M.	Dec. 11 12:00 P.M.	Dec. 11 12:20 P.M.	Dec. 11 1:40 P.M.	Dec. 11 2 - 2:30 P.M.
Time Interval	hrs.		1	1 3/4	3/4	4 1/2	16 1/2	1 3/4		3	3/4	2	11 3/4	1/2	2	1/4	1 1/4	1/2
STATION 38																		
Water Level	in.				41.0						41.0							42.0
Bed Elevation																		
N. Pier	in.		39.8			39.0		38.5				39.1	38.1		36.8		38.9	
S. Pier	in.		39.7			38.9		40.0				40.1	38.9		39.3		39.3	
Mean	in.		40.2			40.0		40.6				40.3	39.8		39.9		40.4	
Max. Scour																		
N. Pier	in.		1.2			2.0		3.8				1.9	2.9		5.2		3.1	
Depth S. Pier	in.		1.3			2.1		2.3				0.9	2.1		2.7		2.7	
Mean Depth	in.		0.8			1.0		1.7				0.7	1.2		2.1		1.6	
Time		Dec. 9 1:30 P.M.	Dec. 9 2:20 P.M.	Dec. 9 2:30 P.M.	Dec. 9 5:00 P.M.	Dec. 9 9:30 P.M.	Dec. 10 2:00 P.M.	Dec. 10 3:30 P.M.	Dec. 10 4:00 P.M.	Dec. 10 7:00 P.M.	Dec.10 7:45 P.M.	Dec. 10 9:40 P.M.	Dec. 11 9:50 A.M.	Dec. 11 10:00 A.M.	Dec. 11 11:30 A.M.	Dec. 11 12:20 P.M.	Dec. 11 1:50 P.M.	Dec. 11 2:20 P.M.
Time Interval	hrs.		1		2 1/2	4 1/2	16 1/2	1 1/2	1/2	3	3/4	2	12		1 1/2	1	1 1/2	1/2

CHAPTER 3

SCOUR AT RIVER SPURS

Introduction

The depth of scour to be expected around river spurs and the position and extent of the scour hole are of utmost importance in the building of these river training devices. River engineers are guided by experience and a few rules but they admit that these rules are very rough. (Ref. 7, p. 104). The following series of experiments was designed to provide both qualitative and quantitative data on scour to be expected around river spurs for certain different conditions of river flow and for spurs with different side slopes. Although river spurs usually have side slopes of 1 : 2, the approximate angle of repose for self-launched rock, i.e. rock which has fallen into a scour hole after its underlying non-cohesive support has eroded away, they may be built with flatter ones. Special reason for interest in steep side slopes is that vertical exaggeration compels their use in models.

Three separate tests were run. In the first two the same river attack condition was devised for each of the four spurs and the only difference was in the discharge used; virtually, the attack condition (Fig. 24) represented a limiting case when a river has embayed behind a spur and runs along it as a guide bank. In the third (Fig. 66) the spur spacing was changed slightly and the river was remade to represent a reach canalised by means of spurs so that attack was roughly

perpendicular to each spur.

Even with the simple conditions of these tests the amount of data to be collected for a possible quantitative regime analysis of all possibilities proved to be very large.

The increasing amounts of data collected as the experiment progressed despite the relative simplicity of the spur layout mark the model-maker's gradual realization of the great complexities and numerous variables involved. For instance, Test 3 is the only one in which continuous readings of scour around the spurs were made.

Special Materials and Apparatus

River tray inlet The inlet was devised (Fig.20) so that water would strike the first spur at about the angle of attack on the others. The collection of strips of metal and plywood of Fig.20 was later replaced by an equivalent structure of plywood and canvas.

Sand Because clay lumps were objectionable the central 8-ft. portion of the river tray was filled with sand whose grain size distribution is shown on Fig. 21. On both side of this strip was the finer sand mentioned in Ch. 1 and just against the west wall was a 3-ft. strip of the old coarser sand-clay mixture.

Sediment analyzer A Rapid Sand Analyzer, obtained through the U.S. Corps of Engineers, enables the quick production of a grain size analysis through observation of the fall velocities of the particles. A maximum of about 3 gms. of material may be analyzed at once.

Spurs Four concrete spurs, best visualised from Fig. 68, were used. All were 8 inches high and 20 inches along the top with noses in the form of half a cone, the slope of the cone being the same as the slope of the sides. The side slopes of the four spurs were: 1:4, 1:2, 1:1, and 1:1/2, in which the 1 is vertical; these spurs are numbered 4, 3, 2, 1, in this report. Usually the spurs were extended in length by placing a thin sheet of some material behind them in the same plane as the spur side.

Bank protection Pieces of burlap sacking served as a pliable, easily-placed protection against undesired erosion of sand banks.

Electric timer A timer connected in series with the sand feeder kept a record of the total time during which the feeder was operating.

Test 1

Procedure Water with a sand charge of about C=22 was run in a straight channel cut in the new sand till a flood plain (Fig. 22) had developed and fairly steady regime had become established. Technical difficulties during this stage caused discharge to fluctuate from 0.03 to 0.10 cusecs so the regime, as in nature, was an average. With the flood plain established the four different spurs were set at uniform spacing, as shown in Fig. 23, so as to compel the flow to develop a sinuous course that would give approximately the same attack conditions on each spur. Burlap bank protection was used to stabilise the sinuosities when they had achieved an extreme enough state to cause flow to run along the shanks; the burlap continued at 1 upon 2 well beneath the bed.

During the flood plain formation an attempt was made to obtain a somewhat more definite flow channel. The method used was to raise the outlet crest by 0.25 inches, wait for aggradation of the channel to occur, and then drop the crest. As might have been expected from the characteristics of a flood plain in sand the definite eroded channel that formed lasted only a few hours and a normal flood plain re-established itself.

Conditions for observations were considered satisfactory when Spur 1 had its top 1 inch above water level for 0.09 cfs. and other spurs were from 2 to 3 inches above the water surface.

After the channel was judged to be in the regime the following data were taken: elevations of water surface along the stream, photographs of contoured sand surface around each spur, and notes on depth and position of deepest scour holes.

The water surface profiles were plotted in two different ways (Fig. 33) in this and the succeeding experiments, viz. straight down the length of the tray and along the path taken by the stream. The distances along the stream were measured off maps like Fig. 23.

Contours were drawn on the stream bed with an ordinary cake decorator filled with cake icing. While the stream was running the water level was marked at each spur. The outlet was then blocked and the tray filled until the highest water level marked was attained. After drawing the contour line at that point by following the sand-water interface the water was lowered until the level of the next highest desired mark was attained and the process was repeated. The contour interval was 2 cm.

For other details of this process see the Appendix, Section G. Two photographs were taken from opposite directions of each spur area after the contours had been laid. (Figs. 25-32). The two photos partially compensate for the distorted image that perspective produces in any one photo.

During this test, unsuccessful attempts were made to photograph the concentration of flow around the spurs and the movement of the bed near the spurs. These are described in Section F of the Appendix.

Experimental data and general observations The figures and tables referred to in this section and under 'procedure' contain a summary of most of the data. The following are taken from notes made during the experiment. The time measurement, frequently mentioned in the following pages, refers to the total time during which the full discharge had been flowing. However after the 270 hour mark, at which time the spurs were set in, all succeeding time intervals were measured from that instant.

1. The initial slope on the sand surface of the whole tray was 0.005.

Initial Conditions

2. As for the model experiment, a channel (this time 24 inches wide) was cut down the centre of the tray and the bottom of this channel was smoothed out after the water had started to run down it.

3. Discharge was started at 0.02 cfs. and increased in jumps of approximately 0.02 cfs. to 0.09 cfs. in 3 hours.

4. Within 20 hours the sides of the stream had caved slightly all along the stream and a slight meander had started, caused apparently by uneven sand distribution from the feeder. (It is true that a stream will start to meander without the activity of an outside agency such as a poorly balanced sand feeder but in this case the uneven sand distribution materially hastened the process.)

Meandering Apparently Caused by Unbalanced Sand Feed

An attempt to stop the meandering was made by straightening the sides and raking the bed until it was even.

5. See Fig. 33 for the water surface elevations at 24 hours.

6. At 24 hours, the height of banks ranged from 2-1/4 inches at Sta. 10 to 3 inches at Sta. 35.

7. By the 26 hour mark another meander had formed with a half length of 9 feet.

8. Meandering became well-developed during the period 26 - 40 hours. (once again the sand had distributed unevenly from the feeder).

9. It was first noticed at 40 hours that there was a noticeable drop in downstream water level just after the removal of sand from the stilling basin.

Trouble With Outlet

10. Sometime between 48 and 64 hours there was a big drop in the downstream water level control. The resulting erosion completely changed the bed pattern. Elevation

11. Between 64 and 127 hours there were more difficulties with the sand spreader and with the outlet being too high.

12. The spurs were set in at 270 hours. Spurs

Tabulated results Tables 7 and 8 were prepared to present quantitative observations for future use and for discussion in Chapter 5. Table 9 is a log of the whole procedure with cross-references between events and the figures and pages that describe them.

TABLE 7

RECORD OF CHARGE Test 1

Time* (Hrs.)			Charge	
Between	And	Interval Hrs.	Entering Tray	Leaving Tray
6	23	17	22	44
23	47	24		40
71	95	24		23
142	167	25		22
167	191	24		22
191	215	24		24
215	239	24		25
239	263	24		26
311	335	24		24
461	485	24		21
485	509	24		19
557	581	24		18
581	605	24		19
605	629	24		22
725	750	25		25
750	773	23		26
773	797	24		22
840	863	23		24
890	912	22		30
912	984.5	72.2		20
984.5	1010	25.5		21
1010	1032	22		18
1032	1056	24	22	22

There may possibly be an error of as much as 40 hours in the times shown in the middle half of this table because at various times the flow was stopped and started during this period. The intervals and the charge values recorded are correct however.

A charge of 1 = 0.20 #/hr. of dry sand for Q = 0.09 Cfs.

* Time measured from moment spurs set in.

TABLE 8

DEPTH OF SCOUR HOLES Test 1

Station	Spur**	Location*	Depth of Bed Below Water Level cm.
9	2	A	9
		B	5
19 1/2	3	A	8
		B	6
		C	8
28 1/2	4	A	6 1/2
		B	5
		C	8
39	1	A	10
		B	5
		C	12

* The three positions at which the depths of scour were recorded are:

A. The deepest hole, usually near the junction of the extension to the spur and the burlap sacking, e.g. Fig. 28. Here the course of the water suddenly changed from a smooth curve to a path parallel to the spur.

B. At the nose of the spur.

C. At the opposite bank where the jet of water which had been flowing parallel to the preceeding spur suddenly struck the burlap bank protection or, at Sta. 39 (Fig. 25), the sheet metal protection, and changed direction.

** The spurs are numbered according to the steepness of their side slopes with Number 1 having the steepest slope.

TABLE 9

LOG AND INDEX Test 1

Time Hrs.	Event	Page or Figure
0	Flow started down 24" wide channel.	P. 41
3	Q = 0.09 Cfs. C (added) = 22.	P. 42
20	Sides beginning to cave.	
	Slight meander observed.	P. 42
24	Water surface elevation.	Fig. 33
63	Sketch of stream bed.	Fig. 22
20 - 127	Difficulties experienced with the sand spreader and with the level of the outlet.	P. 42
270	Spurs set in.	P. 43
	Time Measurement Restarted.	
0	Spurs set in river bed.	P. 43
	Q = 0.09, C (added) = 22.	
1.5	Banks straightened and set at 7 and 13 ft.	P. 40
	Final adjustment to outlet elevation made.	P. 40
About 70	Banks between spurs protected with burlap sacking.	P. 39
825	Problem of uneven sand distribution solved.	Appendix

TABLE 9 - continued

LOG AND INDEX Test 1

Time Hrs.	Event	Page or Figure
913	Sketch of river tray and spurs.	Fig. 23
1037	Water surface elevations.	Fig. 33
1058	Flow stopped.	
	Record of amount of sand being swept into outlet basin.	Table 7
	Record of position and depth of scour holes.	Table 8
	Photos of contoured surface.	Figs. 25 - 32

Test 2

Procedure With the spurs in the same position as in the last test and the sand load also the same, the stream discharge was increased to 0.45 cfs. to represent high flood conditions. When after 62 hours the stream had not reached stability the sand load was increased to five times the previous amount which then made the charge equal to 22 again, and the stream soon became stable.

During Tests 2 and 3 the water did not flow continuously but was turned off for the night because of uncertainty that the pumps would remain steady at this higher discharge and because dredging and drying facilities available could not handle the large amount of sand transported by the stream if it were run longer than 7 or 8 hours out of each 24.

Full discharge was attained within 10 or 15 minutes of starting the pumps; another 5 or 10 minutes elapsed after the pumps had been turned off at the end of the day until only a trickle of water remained in the tray. The sand feeder and electric timer were turned on as soon as Q equalled about 0.30 cfs. and were stopped when the pumps were turned off. The times recorded for the experiment were taken from the electric timer. The measurement of discharge was estimated to be accurate to within 0.05 cfs.

In addition to measurements similar to those made in Test 1, cross-sections of the river were taken (Figs. 35 - 37) after equilibrium had been reached and a few cross-sections of the dunes along the bed

(Figs. 38, 40) were taken after the water had ceased to flow. Figures 34, 39 and 41 show the locations of the various sections. With the exception of the cross-sections of the dunes and of the three sections taken just downstream of the spurs the depths were measured by lowering a rule into the running water until bottom was reached. The others were obtained when the bed was dry by measuring downward from a 2-meter stick set level across the station. The latter levels are related in the figures to the water surface level prevailing just before the flow was turned off.

The photographs of the contours (Figs. 42-45) were taken from as directly above the area as was possible with the equipment available, in an effort to lessen perspective distortion. The metal tapes in the pictures show the sizes of the scour holes.

Experimental data and general observations: 1. During a 2-hour period the discharge was gradually raised from 0 to 0.45 cfs.

2. The headlands behind the spurs had been above water for the 0.09 cfs. flow, but the increased flow covered these areas. Immediately sand began depositing on these shallow areas manifesting itself in the form of an 1/4 to 1/2-inch thick layer with a flat surface moving downstream over the headland. This combined with gradual slope-flattening (after 12-1/2 hours) to again raise the headlands above the water surface. Within 35 hours there were exposed areas behind all four spurs.

Formation of New Headlands

3. The spur at Sta. 39 was set too low for this flow with the result that it was overtopped. Between 1/2 and 1 cm. of water flowed over the top. The extension to the spur was not over-topped.

Spur 1 Over-topped

4. Sometime near the 55-hour mark it was noticed that the scour hole just in front of spur 1 at Sta. 39 had decreased in depth by 2 or 3 inches since last observed a few days previously. This may have been caused by a change in position of the burlap sacking just upstream from the hole.

Change in Scour Depth

5. Consideration of the relatively unchanging water surface profiles and closeness of values of charge entering and leaving the tray formed the basis for the judgement that stability had been attained at the 37-hour mark of the second half of the experiment.

Stability

6. The scouring action at the spurs built up ridges of sand just on the outside of the scour hole. These ridges were most prominent at Sta. 19-1/2, Spur 3, but could also be seen at the other spurs. (see Figs. 42 - 45)

Sand Ridges

7. The careful measuring of water surface elevation along the thalweg (see Fig. 46) shows a marked difference in slope in various parts of the channel. In particular flatter slopes occurred along straight stretches than around curves. Leopold (Ref. 4) noticed this same phenomena in

Variable Slope

meandering rivers.

8. The figures and tables following contain a record of stream cross-sections, water surface elevation, daily charge, final depths of scour, an inspection of the dry bed and the surface contours of the scour holes.

Tables
Figures

Notes on stream bed After the stream had reached equilibrium an examination of the dry bed revealed several curious features. Notes and cross-sections describe the bed at several stations.

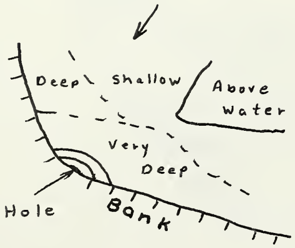
1. A section through sand dunes, Sect. R-R (Fig. 34) was taken along the bed about 1 ft. from Spur 2 and parallel to it (Fig. 38). This section takes in all size ranges of sand dunes found in the tray.

Station
8

2. There were no dunes on the steep bank just at the sharp bend upstream of Spur 2, nor were there any dunes in the deepest part of the scour hole. There were dunes, however, 1/2 - 1 cm. high, along the spur nose.

3. The marked change on the river bed at Sta. 15 as the water suddenly changed direction, is shown in this sketch.

Station
15



4. Two cross-sections, Sects. S-S and T-T, (Figs. 34 and 39) were taken at right angles to each other in the area approaching Spur 3. (Figs. 38, 40). The longer section, Sect. T-T, is indicative of all of the shallow area upstream of the spur. Another cross-section, Sect. U-U (Figs. 34, 41), was taken beside and downstream from the nose of the spur (Fig. 40).

Station 19-1/2

As with the first spur, no dunes were present in the deepest hole but dunes 1/2 - 1 cm. high bounded the nose.

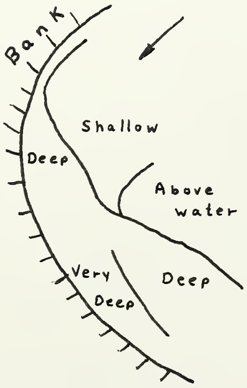
5. At Sta. 22 the bed resembled that at Sta. 15 but the features were not nearly so distinct.

Station 22

6. Although there were no dunes in the deepest hole along Spur 4, in the hole by the opposite bank dunes 1/2 - 1 cm. high were found. At the spur nose the dunes were up to 1/2 cm. high.

Station 28-1/2

7.



Station 34

Station 34

8. There were no dunes in the deepest hole at Spur 1,
nor in the hole by the opposite bank, nor on the downstream Station
side of the spur where the water had been overtopping it. 39
The dunes at the nose were very flat.

Tabulated results Tables 10, 11 and 12 were prepared to present quantitative observations for future use and for discussion in Chapter 5. Table 13, is a log of the whole procedure with cross-references between events and the figures and pages that describe them.

TABLE 10

MEASURED WIDTHS AND DEPTHS AT 43 HOURS Test 2

(See Fig. 47 for location of dimensions)

Location	Depth cm.	Location	Width in.
a	13	a	28
b	16 1/2	b	19
c	10	c	15
d	10 1/2	d	39
e	10	e	19
f	11 1/2	f	15
g	11 1/2	g	36
h	9	h	13 1/2
i	10	i	20
j	10 1/2	j	48
k	9	k	26
l	10	l	18
m	11 1/2	m	19
n	18	n	24
o	19*	o	21
p	13	p	30
q	12 1/2	q	21
		r	46
		s	26
		t	19
		u	43
		v	26
		w	17
		x	17
		y	21
		z	12
		0	18

The dotted line on the map represents the edge of what appeared to be the deep water channel at the time when measurements were made. Measurements between solid lines give the total surface width of the channel.

* At this point the scour depth was once 20 cm.

TABLE 11

RECORD OF CHARGE Test 2

Time (Hrs.)			Charge	
Between	And	Interval Hrs.	Entering Tray	Leaving Tray
1.4	5.7	4.3	4.4	30
5.8	13.1	7.3		20
13.1	20.1	7.0		24
20.1	28.6	8.5		24
28.6	35.8	7.2		29
35.8	43.1	7.3		19
43.1	52.4	9.3		22
52.4	61.8	9.4	4.4	20
	Time restarted			
0	5.9	5.9	22	22
5.9	13.6	7.7		20
13.6	20.8	7.2		18
20.8	28.1	7.3		21
28.1	37.0	8.9		25*
37.0	44.6	7.6	22	20

* This figure is in doubt

A charge of 1 = 1.0 #/hr. of dry sand for Q = 0.45 Cfs.

TABLE 12

DEPTH OF SCOUR HOLES Test 2

Station	Spur**	Location*	Depth of Bed Below Water Level cm.
9	2	A	16 1/2
		B	7
		C	10
19 1/2	3	A	12
		B	7
		C	9
28 1/2	4	A	9
		B	7
		C	10
39	1	A	20
		B	11
		C	12 1/2

* See table 8 for the location of A, B, and C.

**The spurs are numbered according to the steepness of their side slopes with Number 1 having the steepest slope.

TABLE 13

LOG AND INDEX Test 2

Time Hrs.	Event	Page or Figure
0	Discharge of 0.45 Cfs. led into same channel as in last experiment.	P. 49
	Sand being fed in at the rate of 4 1/2 lbs./hr. (C = 4.4).	
	Sand depositing on shallow areas behind spurs.	P. 49
7 12 1/2 19 28 1/2	Measurements taken of water surface elevation.	
35	Exposed areas found behind all four spurs.	P. 49
35 1/2 43 52 58 1/2	Measurements taken of water surface elevation.	
	Plot of channel slopes for 0-58 1/2 hours.	Fig. 48
55	Significant decrease in depth of scour hole at Sta. 39.	
61.8	Time measurement restarted.	
0	Amount of sand added increased to 22.7 lbs./hr. (C = 22).	P. 48

TABLE 13 - continued

LOG AND INDEX Test 2

Time Hrs.	Event	Page or Figure
5 1/2 13 1/2 20 1/2 28	Water surface measurements taken.	
21 1/2	Discharge = 0.6 - 0.7 Cfs. for one-quarter to one-half hour.	
36.8	Water surface measurements taken.	
37.0	Stability judged to have been reached.	P. 50
38.8 to 40.5	Water slope measured very thoroughly.	Fig. 46
	Plot of channel slopes for 5 1/2 - 39 1/2 hrs.	Fig. 49
41.5 to 43.0	Map of river drawn and depths of scour holes measured.	Fig. 47 Table 10
42.5 to 43.7	Cross-sections taken in various places.	Figs. 34 - 37
47.9	Flow stopped.	
	Photograph of dry bed.	Fig. 24
	Record of charge.	Table 11
	Notes on stream bed and sites where cross-sections of sand dunes were taken.	P. 51
	Cross-sections of sand dunes.	Figs. 38 - 41

TABLE 13 - continued

LOG AND INDEX Test 2

Time Hrs.	Event	Page or Figure
	Record of depth of scour holes.	Table 12
	Photographs of contoured scour holes.	Figs. 42 - 45

Test 3

Procedure The positions of the spurs for this test are shown in Figs. 50 and 66-68. The inlet was unchanged but the banks were brought in on both sides to leave a 6-ft. wide channel and there stabilized with burlap sacking except from Sta. 38 downstream where the banks were protected with boards. The change was made in order to force the running water to strike the spurs approximately at right angles.

Once again the experiment was continued until the stream was in regime but this time continuous readings were taken of the scour depth at the spurs to see if, and how, scour depth varied with changes in the stream as it strove towards equilibrium.

An amplitude indicator was tried as a quick method of taking measurements of water surface elevation at various spots along the tray. At first it worked exceedingly well but difficulties arose that caused its use to be discontinued. The Appendix, Section H, gives an account of the trial and some suggestions for future use.

The profile, Sect. D-D and cross-sections, Sects. A-A, B-B, C-C (Fig. 61, 62, 63), of the bed of the cut-off channel formed between Stations 9 and 19 were found by measuring the elevation of the dry bed with a surveyor's level and rod.

An attempt was made to measure the slope of water surface across the stream on a bend but the results were inconclusive because the method of determining elevation was not precise enough to detect the small

differences being measured.

Time measurement was taken from the electric timer and was also a record of the total time during which Q equalled about 0.30 cfs. or more.

This test was run simultaneously with the cut-off experiment described in the next chapter.

Ridges at Spur Noses

Experimental data and general observations 1. Two or three ridges running around and past the noses of each of the spurs were formed at various times during the experiment. Sketches, (more or less to scale) at 10.9 and 14 hours show these ridges early in the experiment when they were most pronounced (Figs. 51 - 53). The photographs (Figs. 54 - 57) taken at the end show much less distinct features.

2. While nearly all the banks were protected from the start it was not until the few remaining spots were covered that the amount of sand being swept out of the tray began to correspond to that entering.

Burlap Protection

3. When a piece of burlap sacking protecting the stream bed at the nose of the rigid guide at Sta. 9 was removed (time - 63.8 hours) the scour depth immediately increased from 20-1/2 cm. to 23-1/2 cm., the depth of the tray bottom. Thereafter the tray bottom at that point was bare of sand.

4. Unfortunately, although a comparison was made between level readings and water surface elevations found by means of the amplitude indicator, these were not referenced to subsequent level readings so that absolute elevations for the two periods can not be compared.

5. Greater fluctuations in water levels along the tray occurred (Figs. 58 - 60) than expected from the steadiness of the water levels during Test 2. The last two slope measurements at 112.5 and 114.6 hours were done with particular care and do correspond to a large degree, so that part of the difference in plots of water level at previous times may be attributed to observational error. It is unlikely, though, that an entire set of readings would be either too high or too low, as would have had to have been the case if the water surface profile actually had been the same at, say, 110.5 and 112.5 hours.

Fluctuations in Water Level

6. The total times required to take a complete set of levels down the tray were recorded for 110.5, 112.5 and 114.6 hours. They were 19, 17, and 13 minutes, respectively. It is possible that in this time fluctuations of water level could take place.

7. The cross-sections and profile of the cut-off above Spur 1 at 109 hours, together with the map showing

Flat

Area at Cut-off

their location, (Figs. 61 - 63), reveal how curiously flat was an area of sand extending under the path of apparently greatest flow. The interval of time during which this area was flat was not recorded but the last photo of the cut-off (Fig. 93) at 43 hours shows dunes on the bed, and at 118.4 hours this area, though still generally level, was broken by short, flat dunes (up to 1/8 inch high).

Limit of Bed Movement

8. During the final hour in which the full discharge was flowing a sketch was made of the stream bed in an attempt to define the limit of bed movement on each side of the channel. The decrease in movement to a very small amount was rather sudden over an area of a few inches so that defining a boundary was not as arbitrary as it might seem (Fig. 64).

Fluctuation in Charge

9. The daily fluctuation in amount of sand leaving the stream bed (Table 14) had no counterpart in the other experiments. Some relation to water surface profiles is seen by comparing the profiles taken at 104.0, 106.8, 108.8 hours (Fig. 59) with those taken at 110.5, 112.5, 114.5 hours (Fig. 60). The general lowering of the water surface (and presumably the bed) between 104.0 and 108.3 hours is much less than between 110.5 and 114.6 hours, and of the two periods enclosing the above intervals the latter

had a charge twice as great.

If the water surface elevation does follow the bed elevation then the final three plots (Fig. 60) show that between 110.5 hours and 112.5 hours bed degradation was considerably higher than between 112.5 and 114.6 hours. This would mean that charge fluctuates not only daily but hourly (this speculation is subject to the possible errors noted under item 5).

Position of Deepest Scour

10. The position of the deepest scour at the spurs seemed to depend upon the path of the water approaching the obstacle, except for Spur 4 at Sta. 37. Here the deepest hole was always found 1 to 3 inches downstream from the extreme tip of the spur nose. (Occasionally the scour hole would extend at the same depth, back a few inches around the nose). This was the final position of scour holes near the other spurs.

When the water first started flowing it followed a very tortuous path, hugging the protected banks as it wound between spurs.

Change in

The depths of scour hole at the spurs during the first few hours were not recorded; however the author attests to the fact that depths between 20 cm. and 22 cm. were attained at Spur 2. At one time it was necessary to

extend the side and nose surface plane of the spur downward with a piece of sheet metal since water was washing beneath the model. Figure 65, a sketch at 22 hours, or 14-1/2 hours after the water had started flowing across the cut-off (Ch. 4) shows deep channels along the banks leading to Spurs 1 and 2 and the concentration of flow on the upstream shanks of 3 and 4. Gradually the stream formed a straighter path so that the total flow did not strike each spur. The sketch (Fig. 64) of the area of bed movement and the final photographs (Figs. 66, 67, 68) indicate the path of flow at the end of the experiment.

Path of Water

The position of the deepest scour was on the upstream shank of the first three spurs at the beginning. At 27.1 hours the hole at Spur 3 had moved until it was just downstream of the nose and remained there until the end except at 68.0 hours when it was observed to be on the shank again. At 41.6 hours the deepest hole at Spur 2 was downstream of the nose, and remained there until 94.9 hours except for a short interval at 75 hours. Except for two readings at 30.3 and at 36.4 hours the scour hole at Spur 1 was not observed downstream of the nose until 54 hours. There it stayed.

Change in Scour Hole Position

Large fluctuations in depth of scour took place both when the scour holes were on the shank and when they

were at or downstream of the nose.

Tabulated results Tables 14, and 15 were prepared to present quantitative observations for future use and for discussion in Chapter 5. Table 16 is a log of the whole procedure with cross-references between events and the figures and pages that describe them.

TABLE 14

RECORD OF CHARGE Test 3

Time (Hrs.)			Charge	
Between	And	Interval Hrs.	Entering Tray	Leaving Tray
0	10.9	10.9	22	23
22.1	28.6	6.5	│	44
36.7	43.2	6.5	│	38
43.2	48.3	5.1	│	28
48.3	54.1	5.8	│	24
54.1	62.0	7.9	│	18
62.0	69.0	7.0	│	15
69.1	73.4	4.3	│	23
82.2	88.2	6.0	│	29
88.2	95.0	6.8	│	19
95.0	102.2	7.2	│	31
102.2	109.0	6.8	│	15
109.0	117.2	8.2	22	30

A charge of 1 = 1.0 lbs./hr. of dry sand for Q = 0.45 Cfs.

TABLE 15

MAXIMUM DEPTH OF SCOUR HOLES Test 3

Station	Spur**	Location*	Depth of Bed Below Water Level cm.
19	1	A	22
		B	14 1/2
25	2	A	19 1/2
		B	14
31	3	A	15
		B	15 1/2
37	4	B	12

* A designates the greatest depth found along the shank of the spur.

B designates the greatest depth found at, or just downstream of, the the nose of the spur.

** The spurs are numbered according to the steepness of their side slopes with Number 1 having the steepest slope.

TABLE 16

LOG AND INDEX Test 3

Time Hrs.	Event	Page or Figure
	Spurs set in new positions; 0.3-0.45 Cfs. of water run for about an hour to smooth out bed.	Fig. 50
0	Q = 0.45 Cfs.	
	C = 22	
7.4	Cut-off started.	P. 73
8.1 to 8.9	Q = 0.3 - 0.35 Cfs.	
8.9 to 9.2	Q approximately equal to 0.6 Cfs.	
10.9	Sketch of dunes around spurs.	Figs. 51- 52
14.0	Sketch of dunes around spurs 3 and 4	Fig. 53
22	Sketch of whole tray	Fig. 65
33.1	Remaining exposed banks stabilized.	P. 61
63.8	Piece of burlap on scour hole at guide removed.	P. 61
? - 67.8	Q approximately equal to 0.6 Cfs.	
69 - 90	Attempted to use amplitude indicator to find water level.	P. 60

TABLE 16 - continued

LOG AND INDEX Test 3

Time Hrs.	Event	Page or Figure
	Map of tray showing points where elevation taken.	Fig. 50
85- 90 104-108.8 110.5-114.6	Water surface elevation plotted.	Fig. 58 Fig. 59 Fig. 60
109	Map of cut-off showing cross-section site.	Fig. 61
109	Cross-sections across cut-off.	Fig. 62
109	Profile along cut-off.	Fig. 63
118.4	Three photographs showing flow of water in tray.	Figs. 66 - 68
	Sketch of area of bed movement.	Fig. 64
	Flow stopped.	
	Record of charge.	Table 14
	Photos of spur areas with contour lines.	Figs. 54 - 57
	Record of maximum scour depths.	Table 15
	Plot of scour depths.	Fig. 69

General Results

(a) In every case for similar conditions the greatest scour occurred alongside spurs having the steeper side slopes (see Fig. 70).

(b) Except for Spurs 3 and 4 in the third experiment, greater scour occurred along the shanks of the spurs than at the noses, and with the exception of 3 again, the depths of scour followed in order of steepness of sides (Fig. 70).

(c) Greater scour occurred when the flow was striking the protruding spur at right angles (Test 3) than when it flowed nearly parallel to it (Test 2).

General Conclusions

These experiments gave a very definite indication that greater scour depths occur along steeper rather than flatter slopes. Alone, the data are insufficient for a mathematical analysis of depth versus slope but should prove useful when more information has been compiled.

Whether the position of maximum scour depends on the intensity of the approaching current or on the part of the spur under attack is a question not entirely solved. See Chapter 5 for more on this.

CHAPTER 4

ILLUSTRATED HISTORY OF A CUT-OFF

Introduction

The object of this test was to record the history of development of an assisted cut-off for future study and analysis. The flood plain left from Test 2 had old channels and headlands still available, so prior to Test 3, the first headland was restored as shown in Fig. 71 with the channel running in a large meander bend. Restoration left a starting channel for a cut-off that, at 0.45 cfs., would have about 0.1 to 0.3 inches of water available to run down it; until starting time this channel was blocked by an obstruction shown at the top right-hand corner of the headland in the photo.

A discharge of 0.45 cfs. and an introduced charge of 22 were used throughout the experiment, except where noted, since it was under these same conditions that the previous meander and headland had formed.

Procedure

A series of photos, supplemented by sketches, recorded the progress of the cut-off. These photos were taken with the author's low-priced reflex camera. The camera was mounted on a stand about 9 feet above water surface. All pictures were taken on Panatomic-X film at

F-16. The time of exposure ranged from one to four seconds since the tray was lit only by fluorescent lights, reflections of which can be seen in the water.

To overcome the effects of perspective distortion in the photographs a 2-foot grid of white string was laid down over the area of interest. The string was 0 inches to 4 inches above the water surface.

Measurements of the scour depth below water surface at Spur 1 at Sta. 19 were taken at intervals. The graphical illustration of scour (Fig. 94) gives an indication of the concentration of flow on the spur.

The time recorded for the experiment includes only the intervals during which 0.3 cfs. or more was flowing. (Sand was being fed into the tray during these periods only). The time required to reach this flow from Q=0 cfs. was about 10 minutes.

Measurement of Q was accurate to within 10% when Q equalled 0.45 cfs. For the smaller flows it is possible that the recorded Q was as much as 30% low.

Chronological Description of Cut-Off Progress

(The terms, 'top' and 'bottom', refer to the photographs or sketches, 'left' and 'right' refer to the reader).

The last 3-foot section of protection, along which the water had been forced to flow in a direction perpendicular to the length of the tray, was removed instantaneously, and

within 1-1/2 minutes the first trickle of water had started flowing across the headland. Figure 72 shows a small flow at the 5-minute mark; Figure 73 indicates a slightly greater flow at 20 minutes (ripples in hitherto still water; larger area covered). 1-1/2 Min. 5 Min. 20 Min.

From 0.7 to 1.5 hours Q was only 0.3 - 0.4 cfs. because of difficulties with the pumps, and no water flowed over the cut-off. Nevertheless, continual erosion of the upstream side of the headland took place, causing the deep channel to move inward (see sketches at 15, 40, and 100 minutes, Fig. 74). From 1.5 to 1.8 hours Q equalled approximately 0.6 cfs. and during this period the depth of flow over the cut-off was estimated at 1/8 inches. 1.5 Hrs.

Figure 75, taken at 2 hours, shows a definite channel through which the cut-off is taking place. On the left-hand side of the photograph the main channel can be seen arching away from the headland, thus forming a spot where a point bar could develop. The sketch at 150 minutes (Fig. 74) confirms this shifting of the deep channel to leave a shallow area. 2 Hrs.

A delta-like formation in the deep water downstream of the cut-off as well as a further indentation of the upstream side of the headland, can be seen in Fig. 76 at 3 3 Hrs.

hours. The cut-off has noticeably entrenched itself into the headland.

The following remarks refer to Fig. 77, taken at a small discharge, and a sketch (Fig. 78), made of the dry bed at 3.5 hours, after the flow had been turned off for the day: 3.5 Hrs. The channel above the headland is now shallower than the original meandering channel had been, though still deeper than the cut-off. The deepest portion is still next to the headland since that is the outside of the curve. Sand being transported on the inside of the bend is filling in the old channel, leaving a deep pond just at the top of the picture (Fig. 77). A point bar still under water has appeared in the shallow area marked in the other photos and along it the dunes move parallel to the shore. As noticed in previous experiments the dunes flatten out and become longer in the deepest portion of the channel.

Taken at 4.5 hours, Fig. 79 shows the cut-off 4.5 Hrs. parallel to the axis of the tray and flowing in a fairly straight, definite channel (signs of this happening had first been noticed at 4.3 hours). The top, left-hand tip of the headland has been cut off and the shallow area just to the left of it has increased in size. The build-up of a sand bar to the left of the tray inlet can be observed. Here, too, the dunes are moving parallel to the shore and gradually adding

to the size of the exposed area.

During the period from 3.5 to 6.6 hours discharge control was poor, Q ranging from about 0.35 to 0.45 cfs. and averaging 0.35 to 0.40 cfs. A comparison of sketches (Fig. 80) made at 4.75 and 6.6 hours together with a study of Fig. 81 at 6.5 hours reveals the changes that 6.5 Hrs. occurred in this interval: (1) The entrance of the widened cut-off to the headland has shifted to the left and the cut-off no longer flows parallel to the axis of the tray. (2) The dunes parallel to the left-hand edge of the headland have moved right into shore and emerged from the water to form a point bar. This point bar seems similar to those described on page 288 ff. of Ref. 5.

At 6.6 hours the experiment was shut down to make repairs to the pumps.

Figure 82 taken at 7.1 hours shows a marked 7.1 Hrs. difference in area covered by the cut-off and water again covers the surface of the point bars. This relatively sudden change can likely be attributed to increased flow. For one half hour previous to the taking of the picture a constant 0.45 cfs. had once again been flowing. This picture also shows the position of the deep water channel just upstream of the headland and the shallow water above that.

Figures 80, 83 and 84 at 8.6 and 9.1 hours mark the rapid reduction of the headland to a small island in the left centre of the picture. Water covers the entire right-hand portion, though shallower to the extreme right than in the central 3 to 4 foot section where the water was about 1 inch deep at 8.6 hours. The southern edge of the high area is extended about 2 feet beyond its original boundary. The absence of ripples on the old meander at 8.6 hours indicated that it then carried little water. By 9.1 hours the cut-off channel was itself in the form of a meander loop. 8.6 Hrs.

The marked increase in scour depth at Spur 1 observed at 10.2 hours was caused by the major portion of the flow striking the spur almost at right angles.

Figure 85, at 11.1 hours shows little change and a sketch at 12.6 hours (Fig. 80) reveals only the further shrinking of the island. 11.1 Hrs.

Judging by Fig. 86 at 14.6 hours the cut-off had lowered the water level in the upstream part of the channel. In the photograph the island and point bar now stand out more distinctly against the water. The deep channel which had extended west from Spur 1 has now been completely filled.

Figure 87 was taken just after the experiment had been shut off for the day at 14.7 hours when Q equalled 0.09 cfs. This shows the relative depths of water.

A series of four pictures follows. Figure 88 at 21.1 hours was taken when Q equalled 0.45 cfs. After stopping the flow of sand at 21.2 hours, 89, 90 and 91 were taken at 0.22, 0.09 and 0.045 cfs. By this time there was definitely no flow of water through the old meander loop. Water was flowing along the right bank with a velocity sufficient to begin eroding that bank. This series of pictures describe the cut-off as being 4 - 6 feet broad with a level, dune - covered bottom . 21.1 Hrs.

The broadness of the point bar is a result of the wide shift in direction of flow of the stream which formed it from the direction of the original flow around the headland.

Between 17-1/2 and 23 hours the scour depth at Spur 1 decreased from 19 to 13-1/2 cm. A comparison of Figs. 87 at 14.7 hours and 90 at 21.2 hours reveals the shift in direction of flow responsible for this lessening of attack. The cut-off channel has developed a slight meander with the outside of the bend about 4 feet upstream of the spur. The main stream no longer concentrates on the spur but flows to the right of it.

The final two photos, Fig. 92 at 29.2 hours and Fig. 93 at 35.6 hours, taken after the grid system had been readjusted to the original 2-ft. squares and the right bank 29.2 Hrs.

protected from further erosion by sacking, show little more than a slight lowering of water level below that of preceeding photos.

In time the southern end of the loop would have filled in to form an ox-bow lake if the stream had been run continously. This was not possible, however, and each time the stream was started anew water coming down the cut-off spilled into the old channel just above Spur 1, thus breaking down the beginnings of any berm. Even this action could have filled in the abandoned loop with sand but a long time would have been required.

Suggestions For Future Observations

The series of sketches and photos describe fairly accurately what happened during this experiment, however, the following measures would improve a repetition of the experiment;

1. A movie camera, set to take a few feet of film every quarter hour would greatly add to the illustration provided by the single pictures. The single snaps are still needed for detailed study, though.
2. If the headland were at the bottom end of the tray then a means would exist for measuring the hourly rate of sand being cut away from the area.
3. When some method is found to take water surface elevations quickly and accurately (see discussion on amplitude indicator in Appendix, Section H), a series of elevations should be recorded frequently during the experiment.
4. Cross sections of the developing cut-off would be interesting although these are difficult to obtain accurately in shallow, flowing water.

CHAPTER 5

ANALYSIS OF SCOUR DEPTHS

Introduction

River engineers have rough rules for designing for scour depths to be expected under certain conditions. Blench gives a table based on "zero flood depth" which he defines as "the regime depth of a canal, having the zero bed factor and discharge of the river, and discharging through a breadth equal to that estimated for the flow channel diminished by the obstruction" (P. 105, Ref. 7). This table is for design of aprons, and does not pretend to predict actual maximum scours infallibly.

Andru has gathered scour data from a number of sources and over a wide discharge range together on one plot on which he has drawn two lines, one a best fit line and the other a well-fitting line using regime theory to calculate the indices (Fig. 1, Ref. 8).

The material from the present thesis is tabulated below (Table 17), so that a comparison (Fig. 95 and Table 18) can be made with both Andru's graph and Blench's table. For notation used in the Tables and the rest of this Chapter see "NOMENCLATURE" and Ref. 7.

Data Analysed

Taylor Flats Model, (Ch. 2) Two kinds of scour were present, scour at a pier (the south pier) and scour at a spur nose (slide protection). Because slide protection B caused the greatest scour its data were used.

b was chosen as the width at one-half depth.

Tests 1 and 2, (Ch. 3) The scour here was considered to be scour occuring along a guide bank.

For Test 2 the value of b could be found from the cross-sections taken during that experiment but for Test 1 the width had to be estimated from photographs. Only two examples are included from Test 1 because estimation of width at the others was considered too inaccurate.

Test 3, (Ch. 3) There were two types of scour in this test, flow past a spur nose and flow impinging at right angles on an obstruction. Difficulty was encountered in estimating q for the right-angled attack on the shanks of the spurs. It was finally judged as three-quarters of total discharge divided by the length of spur since in the initial stages of the experiment when the shank attack was the greatest most of the flow hit the shank of each spur. For attack on the noses $q = \frac{Q}{b}$ as for the other tests.

Tables and graphs Table 17, 18 and Fig. 95 analyse the test data in terms of conventional regime parameters so need no explanation. Although both Blench's and Andru's work are based upon 'zero bed factor' and 'zero flood depth' Table 18 adds columns to analyse in terms of bed factors found from sectional dimensions and presumed discharge intensities, i.e. $d_s = \frac{q^{2/3}}{F_b^{1/3}}$. This was done because Ref. 7 points out that scour estimation from zero flood depth is not yet fully justified.

Results and Conclusions

The plotted points fit Andru's graph about as well as his own points and show, as he also agreed, that different types of obstacles require different fitting lines.

Table 18 shows a comparison between the ratios of scour depth to zero flood depth obtained in this experiment and those given by Blench. (Ref. 7). The maximum values measured fall within the ranges he has given, except for scour at piers which are much lower in these experiments.

The side-slopes of the spurs influence scour depth although this has not been mentioned by either Blench or Andru. This factor should merit further attention.

The figures enclosed within the heavy black lines show a comparison of d_s/d_{fo} for right-angled attack in spur shanks and noses. Judging by the figures for Spurs 1 and 2 the greater scour depth found along the shanks was due to a greater intensity of flow striking the spur at that point. The fact that the upstream side gradually shoaled in indicates that spur shanks in similar positions need the greatest protection for initial attack but later on the protection is unnecessary.

F_{bo} depends upon grain size of bed material only and is usually more easily obtained from published experimental data than is F_b. The fact that present practice is based upon using F_{bo} and that analyses can be performed with F_{bo} where F_b can not be readily determined is a valid

reason for continuing to base design on F_{bo} unless using F_b is found to be more accurate. It would be interesting, though, to see the results of a large scale study, such as was done by Andru, using F_b.

TABLE 17

TABULATION OF SCOUR DEPTHS

Test	Location	Condition	Obstacle	Q Cfs.	b Ft.	q= Q/b	d_s Ft.	$F_{bo}^{1/3}$	$d_s F_{bo}^{1/3}$	$F_b^{1/3}$	$d_s F_b^{1/3}$
Peace River Model	Sta. 10	No slide	pier	0.09	1.6	0.056	0.117	1.03	0.12	1.63	0.19
		Slide B	pier	.09	1.4	.064	.167		.17		.27
		Slide B	spur nose	.09	1.4	.064	.258		.27		.42
	Sta. 38	No slide	pier	.09	2.6	.035	.108		.11		.18
		Slide B	pier	.09	2.3	.039	.175		.18		.28
		Slide B	spur nose	.09	2.0	.045	.242		.25		.40
	Sta. 10	No slide	pier	.45	1.7	.265	.275*		.28		.45
		Slide B	pier	.45	1.4	.312	.333		.34		.54
		Slide B	spur nose	.45	1.4	.312	.54		.56		.88
	Sta. 38	No slide	pier	.45	2.8	.161	.258		.27		.42
		Slide B	pier	.45	2.5	.180	.225		.23		.37
		Slide B	spur nose	.45	2.5	.180	.43		.45		.70
Scour Test 1	Spur 2		Shank	.09	1.0	.09	.295	1.04	.31		
	4		Shank	.09	1.0	.09	.213		.22		
Scour Test 2	Spur 1		Shank	.45	1.9	.24	.656	1.03	.68	2.08	1.36
	2		Shank	.45	1.2	.37	.541		.56		1.13
	3		Shank	.45	2.2	.20	.394		.40		.82
	4		Shank	.45	1.7	.26	.295		.30		.61
Scour Test 3	Spur 1		Shank	.45	1.75	.19	.723	1.06	.77	2.35	1.70
			Nose	.45	4.4	.10	.476		.505		1.12
	2		Shank	.45	1.67	.20	.656		.695		1.54
			Nose	.45	3.9	.115	.460		.49		1.08
	3		Shank	.45	1.75	.19	.492		.52		1.16
			Nose	.45	3.75	.12	.509		.54		1.20
	4		Nose	.45	3.6	.125	.394		.42		.93

*Used instead of the 0.35 ft. depth which occurred at the south pier because there the flow was stongly influenced by the model islands.

q vs. $d_s F_{bo}^{1/3}$ is plotted on Fig. 95

TABLE 18

RATIOS OF SCOUR DEPTH TO A STANDARD

Obstacle or Type of Attack	Test	Location	Condition	Q Cfs.	d_s Scour Depth Ft.	d_{fo} Flood Depth Ft.	$Z = \frac{d_s}{d_{fo}}$	d_r Regime Depth	$R = \frac{d_s}{d_r}$
Pier	Taylor Flats Model	Sta. 10	No slide	0.09	0.117	0.142	0.8	0.090	1.3
		Sta. 10	Slide B		.167	.155	1.1	.698	1.7
		Sta. 38	No slide		.108	.104	1.0	.066	1.6
		Sta. 38	Slide B		.175	.112	1.6	.071	2.5
		Sta. 10	No slide	.45	.275	.40	0.7	.25	1.1
		Sta. 10	Slide B		.333	.45	0.8	.28	1.2
		Sta. 38	No slide		.258	.288	0.9	.18	1.4
		Sta. 38	Slide B		.225	.308	0.7	.20	1.1
Spur Nose	Taylor Flats Model	Sta. 10	Slide B	.09	.258	.155	1.7	.098	2.6
		Sta. 10	Slide B		.242	.122	2.0	.077	3.1
		Sta. 10	Slide B	.45	.54	.450	1.2	.28	1.9
		Sta. 38	Slide B		.43	.308	1.4	.20	2.2
	Scour Test 3	Spur 1		.45	.476	.20	2.4	.095	5.0
		Spur 2			.460	.22	2.1	.10	4.6
		Spur 3			.509	.23	2.2	.105	4.9
		Spur 4			.394	.24	1.6	.105	3.8
Right-Angled Attack	Scour Test 3	Spur 1		.45	.723	.31	2.3	.14	5.1
		Spur 2			.656	.32	2.0	.145	4.5
		Spur 3			.492	.31	1.6	.14	3.5
Flow Along Guide Bank	Scour Test 1	Spur 2			.295	.19	1.6		
		Spur 4			.213	.19	1.1		
	Scour Test 2	Spur 1		.45	.656	.38	1.7	.19	3.5
		Spur 2			.541	.50	1.1	.25	2.2
		Spur 3			.394	.33	1.2	.16	2.5
		Spur 4			.295	.40	0.7	.20	1.5

Spur Noses	2.0 - 2.75	Page 105 Ref. 7
Right-angled attack	2.25	
Piers	2.0	

APPENDIX

MOBILE - BOUNDARY MODEL TECHNIQUE

A model maker continually runs into problems connected with the creation and/or operation of his model. Sometimes these difficulties are of a specialized nature such as the control of discharge in the particular equipment with which he is working, or the problem may be a more general one such as the stabilization of stream banks in a model. The following matters of technique were all encountered during the experiments described in this thesis but are considered to be of general interest.

The reader will discover that some of the notes are a record of achievement, while others are a tale of failure. Both should be helpful to a future experimenter.

INDEX TO APPENDIX

A. The use of sand-clay mixtures in a river tray.
B. The use of a hook-gauge and V-notch weir to measure discharge.
C. Obtaining continuous discharge measurements.
D. The stabilization of river banks in a sand tray.
E. The even distribution of introduced charge.
F. Obtaining photographic records of stream flow and bed movement.
G. Drawing contour lines on the surface of a stream bed.
H. Use of an amplitude indicator to measure water surface elevation.

A. The Use of Sand - Clay Mixtures in a River Tray

Purpose - the duplication of nature's gradually erodible banks by using a material composed of both sand and clay for the stream banks and bed.

Results - Because the two materials could not be mixed together evenly lumps of clay remained like boulders in a real river.

There were no facilities either to dry the two yards of clay that were procured for the mixture or to mix the sand and clay together properly. Because the clay seemed to disintegrate under water, it was broken into pieces about 4 cubic inches in volume and spread on top of the sand in the tray, then the whole tray was covered with water and let stand. The next day the two ingredients were mixed with shovels. Later when a channel was cut in the tray and a stream set flowing, it was discovered that the mixing process was far from satisfactory. Large pieces of clay remained as inerodible barriers to the water and even pea-sized pieces rolled along the bed or clustered together as a protective coating in scour holes. Very little clay appeared to be carried in suspension; at no time did the flowing stream form berms of the suspended material as real canals do.

It would be interesting to try a sand-clay material that was thoroughly mixed and in which there were no lumps of clay that would

not pass through a number 10 sieve. The stream, however, builds up its own concentrations of clay in backwash and other still areas so that the problem of inerodible clay pockets would still occur.

B. The Use of a Hook-Gauge and V-Notch Weir to Measure Discharge

Purpose - to measure water flow accurately by means of a 90° V-notch weir.

Results - The discharge computed from the approximate formula for the flow over a V-notch weir $Q = 2.5\, H^{5/2}$ did not compare favorably with either the discharge given by a rotameter in the system or with discharge computed by a volumetric - time measurement.

A three-inch rotameter used regularly for the under-graduate lab, was connected to the system containing one of the weir boxes used on the tray. The curves showing discharge as given by the rotameter vs. Hook gauge reading is shown on the same figure (Fig. 96) as the discharge given by the approximate formula $Q = 2.5\, H^{5/2}$.

A quick check was made by leading water from the weir box into a large measurable tank, thereby measuring both volume and time. The two tests run are plotted on the above-mentioned graph. These latter fall between the former two calibration curves and equal about 90% of the discharge as given by the rotameter. The 90% figure has been accepted in this thesis as being accurate.

C. Obtaining Continuous Discharge Measurements

Purpose - To obtain a continuous record of discharge

Results - The vibrating point limnigraph used could not be trusted to keep a record longer than a few hours.

When the calibration described in Part B was done a calibration was also run on a vibrating point limnigraph which was supposed to give a continuous reading of height of water surface above the weir. The operation of the machine is briefly as follows: The electrically - charged tip of the vibrator is kept just at the surface of the water by the electrical mechanism of the machine. The vertical motion of the vibrator is transferred to a moving roll of paper by means of a pen. Two difficulties caused the abandonment of the use of this machine: (1) the paper often slipped on the moving drum; (2) the pen held enough ink for only an hour or so of operation. Although considerable time was spent trying to correct these conditions absolutely no headway was made.

D. The Stabilization of River Banks in a Sand Tray

Purpose - to prevent the sand banks of a model river from eroding beyond a definite limit without altering other characteristics of the river badly.

Results - The placing of burlap sacking on banks that are to be protected is the most satisfactory device found.

During the model study described in Chapter 2, it was necessary

that the river banks be stabilized after the piers and slide protection were set in because erosion of the non-cohesive sand banks would be quite unlike that of the cohesive shaley river banks.

The plastering of mud on the banks worked for the small flow if a constant watch was kept for the beginning of breaches. At Sta.38, where the stream was wider, paper was used successfully to protect the banks for both small and large flows. At constricted Sta. 10 neither of these would save the banks when 0.45 cfs was turned on; it was necessary to place sheet metal against the banks and around the islands. While this, of course, did protect the sand from eroding there are many objectionable features; sheet metal is not easily bent into the desired shape; its smoothness seems to make water cling to it so that the depth of flow against a bank is always much greater than elsewhere in the channel, and its sharpness makes it dangerous to handle.

During the next experiment burlap sacking was tried as a protective material. It is easily placed in whatever shape desired. In practice the sacking was placed several inches under the bed of the stream on the same slope as the side so that the stream could not erode beneath and behind it and so that if the stream did cling to the sacking the stream channel formed, though deeper than normal, would still have the same side slopes as before. In these experiments the rough sacking (often containing wrinkles) did not seem to cause so great a scour along itself as had been caused by the smooth sheet metal.

E. The Even Distribution of Introduced Charge

Purpose - to add sand to a stream in such a way that this additional charge is all carried down the stream.

Results - The best method found for this purpose was to have the introduced sand fall into a constricted part of the channel.

The sand from the feeder fell from a height of about three feet into the stream. The platform from which the sand was dropped was only 4 inches wide so some method of spreading the sand had to be found otherwise the stream, being about two feet wide at that point originally, simply split and flowed around the ever-increasing pile of sand. The delicate positioning of a cone-shaped spreader onto which the sand fell and was distributed over a wider area worked sometimes but trouble was continually occurring. The final move, which proved to be successful, was to constrict the channel just under the feeder and let the narrow stream of sand fall into the constricted portion. This constriction did distort the channel for a few feet further downstream but at all times the introduced load was evenly carried from that area.

F. Obtaining Photographic Records of Stream Flow and Bed Movement

Purpose - to photograph the direction and concentration of both the flowing water and the moving sand on the bed.

Results - No worthwhile records could be obtained.

In an attempt to obtain photographs of the concentration of flow at the surface of the water time exposures were taken of the following objects floating on water moving at the rate of about half a foot per second; small pieces of white paper, burning corks, corks coated with luminous paint, and corks coated with various flourescent substances (these last were tried under ultra-violet light). The burning corks were the only objects that left a track on the film and these tracks were very untidy because the flare-up of the corks when they were first lighted left a wide jagged track at the beginning while the end of the tracks were faint. This disadvantage added to the uncertainty of the corks always remaining burning and the messiness of working with half-burnt corks cause the project to be abandoned.

It had been hoped that if a track could be obtained with flourescent objects then a flourescent mixture could be imbedded in wax balls and sent rolling along the bottom to be photographed. However, even the flourescent objects on the surface of the water could not be tracked on film.

G. Drawing Contour Lines on the Surface of a Stream Bed

Purpose - to draw lines of equal elevation on the scour holes and to photograph these lines.

Results - A mixture of lard and icing sugar is easy to apply in a thin, controlled line with a cake decorator. The white line is readily photographed.

The use of white string for this purpose was tried but found to be impractical because placing the string took hours to do and because the string could not be made to lay exactly where put when wound around sharp bends.

The possibility of spraying white paint just along the sand-water interface was considered but discarded because the paint could not be easily removed afterward and because the force of the paint jet would disturb the sand.

Cake icing, being slightly sticky, was easily placed in whatever position desired. When a mistake was made or a line came loose from the sand, it could be removed with a small knife and a new length put in.

The icing was removed from the sand afterwards by the flow of water for the next experiment, after the pieces had been manually broken up and partially dislodged.

Contours were drawn by setting the water in the tray at a certain elevation and then following the sand-water interface with a decorator.

H. Use of an Amplitude Indicator to Measure Water Surface Elevation.

Purpose - to discover some quick, accurate method of measuring the slope in a river tray.

Results - Circumstances made the readings taken by the amplitude indicator too inaccurate to be of value.

The amplitude indicator at the Civil Engineering Dept., U. of A.

works on the principle of capacitance. One terminal of the meter is attached to enamel-plated copper wires which are held vertically in the water. The other terminal is attached to a grounding plate resting in the water. When in operation, the enamel acts as the dielectric between the water and the copper. If the copper wires are held steady then the capacitance of the system increases as water level arises. The probes (name given to copper wires and their supports) consist of a device resembling a harp around whose two arms the wires can be wound snugly.

A set of fifteen probes, all the same size and each containing the same number of turns of the copper wire, were made especially for the experiment. They each had stands of brass plate into which they could be screwed. A one-inch length of screw thread was used so that slight changes in the elevations of the probes could be made without disturbing the stand. A test was run on the probes by placing all in a large tank and reading the difference in capacitance indicated on all by a rise in water level. The greatest variation from the average found in this preliminary test was in the range of 3 percent or a possible error in elevation of two milimeters. This was well within the accuracy hoped for.

The first step after the probes had all been set in the desired spots in the river tray (Fig. 50) was to block the tray outlet, fill the tray with water to a short distance above the highest elevation attained by the flowing water during regular runs, and record this 'zero' reading

for each probe. One of the probes had been kept out and with this probe set in a container of water the instrument could be calibrated so that all the readings fell in the dial range.

Thoughtlessness about the working of the indicator led to initial trouble when it was found that the capacitance between lead-in wires connecting the machine to the probes and the water were rendering the readings totally inaccurate. This condition was corrected by seating the amplitude indicator on the tray's moving platform and clipping the short leads from the indicator on to the probes in turn. This caused the total reading time to be longer (a complete set of readings took about ten minutes) but eliminated the extra capacitance.

Because the indicator can measure mean water level the average water level at each probe could be measured to within a fraction of a milimeter. This was very gratifying as it seemed the answer to measuring slopes over short lengths of stream. After an initial check of the readings with a surveyor's level showed a good correspondence, readings of water level were taken for several days with the instrument (Fig.97).

It was discovered that a warm-up period of ten or fifteen minutes is needed after the instrument is plugged in until any readings are taken. Figure 98 shows three sets of readings taken during a short interval of time; one was taken before the machine had warmed up.

After several days the instrument readings were again checked against level readings. This time a discrepancy was found that was

considered to be too large to justify the continued use of the amplitude indicator. Figure 58 shows a set of three comparative readings of water level down the tray, taken at nearly the same time. The readings for each point on the 90-hour plot were taken practically simultaneously, so there was no chance of error because of changing water level.

The following factors are very likely the cause of error in this instrument, other models of which have worked very well in the Grenoble Laboratory of Neypric in France:

1. The water being circulated contained little floating pieces of tar from the waterproofing around the tray. These sticky pieces were observed to be attached to the copper wires and thus the dielectric constant of the capacitor was being changed since water and tar do not have the same electrical properties.

   It should be possible, if some time were spent, to construct small screens to set around the copper wires so that floating debris could be caught without affecting the level of water in contact with the wires.

2. Continually clipping on and off the probes with the instrument leads probably affected the level of the probes so that the 'zero' readings would change. A larger, firmer base or an ingenious method for eliminating the effects of capacitance in long lead wires should be the answer to this.

At one time worry was felt in case the moving bed sand should scour the enamel off the probe wires. If this were to happen the probes would have to be rewound. No evidence of this happening during the time the probes were used was seen but a perforated screen through which water would flow, but which would hold sand back, might be a suitable safety measure.

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